

TITLE OF THE INVENTION

OPTICAL AMPLIFIER AND OPTICAL AMPLIFICATION METHOD

RELATED APPLICATIONS

This is a Continuation-In-Part application of
International Patent Application serial No.
PCT/JP00/01660 filed on March 17, 2000 now pending.

BACKGROUND OF THE INVENTIONField of the Invention

The present invention relates to an optical
amplifier and optical amplification method of
amplifying, at once, a multiplexed signal in which a
plurality of signal light components having different
wavelengths belonging to a predetermined wavelength
band are multiplexed.

Related Background Art

The optical amplifier which amplifies signal light
by guiding to a waveguide doped with a fluorescent
material together with optical pumping light of such
fluorescent material is well known. Such an optical
amplifier is provided in a relay station in an optical
transmission system. Especially, an optical amplifier
used in a wavelength-multiplexed transmission system
for transmitting multiplexed signal light in which a
plurality of signal light components having different
wavelengths are multiplexed optically must amplify the
plurality of signal light components at once at an

equal gain, and also amplify the power of each of the plurality of signal light components to a predetermined target value and output the signal light.

For example, reference 1, K. Inoue, et al.,

5 "Tunable Gain Equalization Using a Mach-Zehnder Optical Fiber in Multistage Fiber Amplifiers", IEEE Photonics Technology Letters, Vol. 3, No. 8, pp. 718 - 720 (1991) is disclosed a technique of flattening the gain of an optical amplifier by an optical fiber using a
10 Mach-Zehnder interferometer. Reference 2, S. Kinoshita, et al., "Large Capacity WDM Transmission Based on Wideband Erbium-Doped Fiber Amplifiers", OSA TOPS, Vol. 25, pp. 258 - 261 (1998) is disclosed a technique in which an optical attenuator with a variable
15 attenuation factor is inserted between the input-side optical amplification section and the output-side optical amplification section of an optical amplifier so as to maintain constant power of signal light input to the output-side optical amplification section even
20 when the power of signal light input to the input-side optical amplification section varies, thereby maintaining the power of signal light output from the optical amplifier at a predetermined target value and simultaneously maintaining constant gain deviation of
25 the entire optical amplifier.

SUMMARY OF THE INVENTION

INS
C1

5 In the technique described in reference 1, however, for example, to keep the power of signal light output from the optical amplifier at a predetermined target value when the loss in the input-side transmission line of the optical amplifier varies due to some reason, and the power of signal light input to the optical amplifier varies, the gain of optical amplification of signal light in the optical amplifier must be changed. 10 If the gain is changed, the wavelength dependence of gain varies. This damages the gain flatness of the optical amplifier, and the plurality of signal light components output from the optical amplifier have different powers or so-called deviation.

002260-97529960

15 INS
C2

15 In the technique described in reference 2, to keep the power of signal light input to the output-side optical amplification section at a predetermined target value by the optical attenuator when the signal light input to the input-side optical amplification section 20 has sufficiently high power, the power must be largely attenuated by the optical attenuator. As a result, the pumping efficiency lowers to degrade the noise factor.

25 The present invention has been made to solve the above problems, and has as its object to provide an optical amplifier and optical amplification method capable of maintaining the output signal light power

and gain flatness without degrading the noise factor even when the input signal light power varies.

In order to achieve the above object, according to the present invention, there is provided an optical amplifier for amplifying, at once, multiplexed signal light belonging to a predetermined wavelength band, in which a plurality of signal light components having different wavelengths are multiplexed, characterized by comprising (1) one or a plurality of optical amplification sections each of which has an optical waveguide doped with a fluorescent material and amplifies the multiplexed signal light by optical pumping of the fluorescent material, (2) an optical pumping light source for supplying predetermined optical pumping light to the optical amplification section, (3) an optical filter capable of changing a gradient $dL/d\lambda$ of a loss L (dB) with respect to a wavelength λ (nm) in the predetermined wavelength band, and (4) control means for controlling an optical pumping light output from the optical pumping light source such that light power after amplification has a predetermined target value, and for adjusting a characteristic of the optical filter to adjust a final gain characteristic.

On the other hand, an optical amplification method according to the present invention is characterized by

comprising the steps of (1) guiding the multiplexed signal light to an optical waveguide doped with a fluorescent material together with predetermined optical pumping light and optically amplifying the multiplexed signal light, (2) guiding at least one of the multiplexed signal light before amplification and that after amplification to an optical filter capable of changing a gradient $dL/d\lambda$ of a loss L (dB) with respect to a wavelength λ (nm) in the predetermined wavelength band and adjusting the gradient $dL/d\lambda$ of the optical filter to reduce a wavelength-dependent gain in the optical amplification, and (3) adjusting an intensity of the optical pumping light to adjust light power after amplification to a predetermined target value.

According to the optical amplifier or optical amplification method of the present invention, even when the input signal light power to the optical amplifier varies, the output signal light power from the optical amplifier can be maintained at a predetermined target value. In addition, even when the gain of the optical amplification section has a wavelength dependence due to variation in input signal light power, the gain flatness of the entire optical amplifier can be maintained by adjusting the gradient $dL/d\lambda$ of the loss L of the optical filter with respect

to the wavelength λ .

This optical filter preferably satisfies

$$L \approx a(\lambda - \lambda_c) + b$$

(where λ_c (nm) and b (dB) are constants) in the

predetermined wavelength band and changes a (dB/nm) to
adjust the gradient $dL/d\lambda$. Such an optical filter can
easily adjust the gradient $dL/d\lambda$. When λ_c is set in the
predetermined wavelength band, the loss L at the
wavelength λ_c in the predetermined wavelength band
always becomes constant. This enables design with an
emphasis on the noise characteristic at λ_c .

The optical amplifier may further comprise a gain
equalizer for compensating for a inherent wavelength-
dependent gain of the optical amplification section.
In this case, the gain equalizer equalizes the inherent
wavelength-dependent gain of the optical amplification
section, and the optical filter compensates for
variation in input multiplexed signal light power.
This makes the gain flatness of the entire optical
amplifier more excellent and facilitates
control/adjustment.

Preferably, the optical amplifier further
comprises a wave number monitor for detecting the
number of signal light components contained in the
multiplexed signal light, and the control means adjusts
the target value of light power after amplification in

accordance with the number of signal light components detected by the wave number monitor. Even when the power of input multiplexed signal light varies due to an increase/decrease in the number of signal light components, the power of each multiplexed signal light component can be maintained constant.

The gradient $dL/d\lambda$ of the optical filter may be adjusted, e.g., 1) on the basis of the detection result from input light power detection means for detecting the light power input to the optical amplification section, 2) on the basis of the detection result from gain detection means for detecting a gain of the optical amplification section, 3) on the basis of power deviation between shortest and longest wavelengths detected by detecting each wavelength and power of signal light components contained in the light output from the optical amplification section, or 4) such that a level difference between ASE light levels detected by ASE light level detection means for detecting an ASE light level of each of wavelengths outside two ends of the predetermined wavelength band of the light output from the optical amplification section. Each wavelength and power of signal light components contained in the light output from the optical amplification section may be detected, and an ASE light level of a wavelength at a shorter wavelength than

detected shortest wavelength and at a longer wavelength than detected longest wavelength may be detected and used for adjustment. In case 3) or 4), a wavelength for which the power deviation or ASE light level is to be detected may be determined on the basis of information related to the shortest and longest wavelengths, which are sent together with the multiplexed signal light.

In addition, when a total transmittance in the predetermined wavelength band of the optical filter is adjusted to a maximum value, the loss L is preferably adjusted to be substantially constant independently of the wavelength. This enables to reduce the noise factor especially when the input multiplexed signal light power is small.

Any one of the above arrangements and methods facilitates adjustment of the gradient $dL/d\lambda$ of the optical filter and realizes the object of the present invention.

The optical filter in the optical amplifier according to the present invention preferably comprises (1) a main optical path which guides the multiplexed signal light and is divided into first to sixth regions sequentially from an upstream side, (2) a first sub optical path which is arranged close to the first and third regions of the main optical path so that optical

coupling of propagation light occurs, is spaced apart from the second region of the main optical path so that optical coupling of the propagation light does not occur, and has a region corresponding to the second region of the main optical path, the region having a length different from that of the main optical path, (3) a second sub optical path which is arranged close to the fourth and sixth regions of the main optical path so that optical coupling of the propagation light occurs, is spaced apart from the fifth region of the main optical path so that optical coupling of the propagation light does not occur, and has a region corresponding to the fifth region of the main optical path, the region having a length different from that of the main optical path, (4) a first temperature adjusting device arranged in at least one of the second region of the main optical path and the region of the first sub optical path, which corresponds to the second region of the main optical path, and (5) a second temperature adjusting device arranged in at least one of the fifth region of the main optical path and the region of the second sub optical path, which corresponds to the fifth region of the main optical path.

On the other hand, in the optical amplification method according to the present invention, preferably,

an optical filter comprising (1) a main optical path which guides the multiplexed signal light and is divided into first to sixth regions sequentially from an upstream side, (2) a first sub optical path which is arranged close to the first and third regions of the main optical path so that optical coupling of propagation light occurs, is spaced apart from the second region of the main optical path so that optical coupling of the propagation light does not occur, and has a region corresponding to the second region of the main optical path, the region having a length different from that of the main optical path, and (3) a second sub optical path which is arranged close to the fourth and sixth regions of the main optical path so that optical coupling of the propagation light occurs, is spaced apart from the fifth region of the main optical path so that optical coupling of the propagation light does not occur, and has a region corresponding to the fifth region of the main optical path, the region having a length different from that of the main optical path is used, and the gain wavelength dependence reduction step comprises adjusting at least one of a temperature in the first sub optical path and a temperature in a region of the main optical path, which corresponds to the first sub optical path, and at least one of a temperature in the second sub optical path and

a temperature in a region of the main optical path, which corresponds to the second sub optical path to adjust the gradient $dL/d\lambda$ of the optical filter.

Each of the first and second sub optical paths and the corresponding main optical path form a Mach-Zehnder interference device. In each Mach-Zehnder interference device, when the temperature of at least one of the optical paths is adjusted, the wavelength dependence of loss in each main optical path can be adjusted. Hence, this optical filter is suitable for the optical amplifier and optical amplification method according to the present invention.

The present invention will be more fully understood from the detailed description given hereinbelow and the accompanying drawings, which are given by way of illustration only and are not to be considered as limiting the present invention.

Further scope of applicability of the present invention will become apparent from the detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will be apparent to those skilled in the art from this detailed description.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic view showing the arrangement of an optical amplifier according to the first embodiment of the present invention;

5 Fig. 2 is an explanatory view of the output-side optical amplification section and optical pumping light source, and Fig. 3 is an explanatory view of the optical filter;

10 Figs. 4 to 6 are graphs showing loss spectra obtained when a phase value $\Delta\phi$ was changed in Examples A to C of the optical filter;

Figs. 7A to 7D are views for explaining the operation of the optical amplifier according to the first embodiment;

15 Figs. 8, 9, and 10A are schematic views showing the arrangements of optical amplifiers according to the second to fourth embodiments of the present invention, respectively, and Fig. 10B is a schematic view showing the arrangement of a modification of the fourth
20 embodiment;

Fig. 11 is an explanatory view of an optical filter and spectrum monitor device in the third embodiment;

25 Fig. 12 is a schematic view showing the arrangement of an optical amplifier according to the fifth embodiment of the present invention, and

Figs. 13A to 13C are views for explaining its operation;

Figs. 14A and 14B are schematic views showing the arrangements of an optical amplifier according to the sixth embodiment of the present invention and its modification, respectively, Fig. 15 is a schematic view showing the arrangement of an optical amplifier according to the seventh embodiment of the present invention, and Fig. 16 is a graph which compares the noise characteristic of the seventh embodiment with that of a conventional optical amplifier;

Fig. 17 is a view for explaining the loss spectrum of a modification of an optical filter used in the optical amplifier according to the present invention; and

Fig. 18 is a schematic view showing the arrangement of an optical amplifier according to the eighth embodiment of the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Preferred Embodiments of the present invention will be described below in detail with reference to the accompanying drawings. To facilitate the comprehension of the explanation, the same reference numerals denote the same parts, where possible, throughout the drawings, and a repeated explanation

will be omitted.

(First Embodiment)

Fig. 1 is a schematic view of an optical amplifier according to the first embodiment. In the optical amplifier 100 according to this embodiment, an optical coupler 130, input-side optical amplification section 111, optical filter 140, and output-side optical amplification section 112 are sequentially connected in series between an optical input terminal 101 and an optical output terminal 102. The optical amplifier 100 also has optical pumping light sources 121 and 122 for supplying optical pumping light to the input-side optical amplification section 111 and output-side optical amplification section 112, respectively, and a control circuit 150 for controlling the light powers from the optical pumping light sources 121 and 122 and the loss spectrum of the optical filter 140.

The optical coupler 130 demultiplexes some components of multiplexed signal light input to the optical input terminal 101, outputs the components to the control circuit 150, and outputs the remaining components to the input-side optical amplification section 111. The input-side optical amplification section 111 receives optical pumping light from the optical pumping light source 121, optically amplifies the multiplexed signal light sent from the optical

coupler 130 at once, and outputs the signal light. The optical filter 140 has a loss spectrum in which the total loss is almost constant in the wavelength band of the multiplexed signal light, and the gradient of loss with respect to the wavelength is variable in the wavelength band. The output-side optical amplification section 112 receives optical pumping light from the optical pumping light source 122, optically amplifies the multiplexed signal light sent from the optical filter 140 at once, and outputs the signal light to the optical output terminal 102.

The control circuit 150 detects the power of multiplexed signal light demultiplexed by the optical coupler 130. The control circuit 150 controls the power of optical pumping light to be output from the optical pumping light sources 121 and 122 on the basis of the power of input multiplexed signal light such that the power of output multiplexed signal light obtains a predetermined target value. The control circuit 150 also controls the loss spectrum of the optical filter 140 on the basis of the power of input multiplexed signal light.

Fig. 2 is an explanatory view of the input-side optical amplification section 111 and optical pumping light source 121. The input-side optical amplification section 111 includes an amplification optical fiber 113,

optical coupler 114, and optical isolators 115 and 116. The optical coupler 114 sends optical pumping light output from the optical pumping light source 121 to the amplification optical fiber 113 and also passes signal light output from the amplification optical fiber 113. The optical isolators 115 and 116 pass light in the forward direction but do not pass light in the reverse direction.

The amplification optical fiber 113 is an optical waveguide doped with a fluorescent material that can be excited by optical pumping light output from the optical pumping light source 121. The fluorescent material to be doped is preferably a rare earth element and, more preferably, Er. Er is preferably doped because signal light in a 1.55- μm band can be optically amplified. At this time, the wavelength of optical pumping light to be output from the optical pumping light source 121 and supplied to the amplification optical fiber 113 is preferably 1.48 μm or 0.98 μm . The output-side optical amplification section 112 and optical pumping light source 122 have the same arrangement as described above.

A preferred example of the optical filter 140 will be described next. Fig. 3 is an explanatory view of the optical filter 140. This optical filter 140 is a planar lightwave circuit formed on a substrate 10 made

of, e.g., quartz, and comprises a main optical path 20,
first sub optical path 21, second sub optical path 22,
heater 51 serving as a first temperature adjustment
means, and heater 53 serving as a second temperature
adjustment means.

The main optical path 20 is an optical waveguide
for guiding light incident on an optical input terminal
11 at one end face of the substrate 10 to an optical
output terminal 12 at the other end face of the
substrate 10 and causes the light to emerge therefrom.
The main optical path 20 has six regions A to F.

The main optical path 20 and first sub optical
path 21 are close and optically coupled to each other
in the first region A and third region C, thereby
forming a first optical coupler 31 and second optical
coupler 32. In the second region B, the optical path
length of the main optical path 20 is set to be longer
than that of the first sub optical path 21, so the two
optical paths are spaced apart from each other. Thus,
the portion of the main optical path from the first
region A to the third region C and the first sub
optical path 21 construct an asymmetrical Mach-Zehnder
interference circuit. This portion will be referred to
as a first Mach-Zehnder interference circuit 41
hereinafter.

Similarly, the main optical path 20 and second sub

optical path 22 are close and optically coupled to each other in the fourth region D and sixth region F, thereby forming a third optical coupler 33 and fourth optical coupler 34. In the fifth region E, the optical path length of the main optical path 20 is set to be shorter than that of the first sub optical path 21, so the two optical paths are spaced apart from each other. Thus, the portion of the main optical path from the fourth region D to the sixth region F and the second sub optical path 22 construct an asymmetrical Mach-Zehnder interference circuit. This portion will be referred to as a second Mach-Zehnder interference circuit 42 hereinafter.

The heater 51 is formed on the second region B of the main optical path 20. This heater 51 adjusts the temperature of the main optical path 20 to adjust the optical path length difference between the main optical path 20 and the first sub optical path 21 in the first Mach-Zehnder interference circuit 41, thereby adjusting the transmission characteristic of the first Mach-Zehnder interference circuit 41. The heater 53 is formed on the fifth region E of the main optical path 20. This heater 53 adjusts the temperature of the main optical path 20 to adjust the optical path length difference between the main optical path 20 and the second sub optical path 22 in the second Mach-Zehnder

interference circuit 42, thereby adjusting the transmission characteristic of the second Mach-Zehnder interference circuit 42'. The heaters 51 and 53 are controlled by the control circuit 150.

5 Heaters may be provided on the second region B of the first sub optical path 21 and on the fifth region E of the second sub optical path 22 in place of the heaters 51 and 53. Alternatively, heaters may be provided on both the main optical path and the first
10 and second sub optical paths. Instead of the heaters, Peltier elements for cooling may be provided.

In this optical filter 1, a loss spectrum $L(\lambda)$ [dB] for light input to the optical input terminal 11 and output from the optical output terminal 12 through
15 the main optical path 20 depend on both a transmittance characteristic $T_1(\lambda)$ of the first Mach-Zehnder interference circuit 41 based on optical coupling between the main optical path 20 and the first sub optical path 21 by the optical couplers 31 and 32 and a
20 transmittance characteristic $T_2(\lambda)$ of the second Mach-Zehnder interferometer 42 based on optical coupling between the main optical path 20 and the second sub optical path 22 by the optical couplers 33 and 34.

25 Generally, a transmittance characteristic $T(\lambda)$ of an asymmetrical Mach-Zehnder interference circuit is

given by

$$T(\lambda) = 1 - A \sin^2 \left(\frac{2\pi(\lambda - \lambda_0)}{\Delta\lambda} + \Delta\phi \right) \quad (1)$$

where λ [nm] is the wavelength of light, A , λ_0 [nm], and $\Delta\lambda$ [nm] are constants determined by the structural

5 parameters of the Mach-Zehnder interference circuit, and $\Delta\phi$ is the phase value that can be set by temperature adjustment. A loss spectrum $L(\lambda)$ of the optical filter 1 is given by

$$L(\lambda) = -10 \log \{T_1(\lambda) \cdot T_2(\lambda)\} \quad (2)$$

10 A gradient $dL(\lambda)/d\lambda$ of the loss spectrum $L(\lambda)$ of the optical filter 1 with respect to the wavelength will be simply referred to as a gradient $S(\lambda)$ hereinafter.

When the constants A , λ_0 , and $\Delta\lambda$ of each of the first Mach-Zehnder interference circuit 41 and second Mach-Zehnder interference circuit 42 are appropriately designed, and the phase value $\Delta\phi$ is changed by temperature adjustment by the heaters 51 and 53 while maintaining an almost constant loss $L(\lambda_1)$ at a predetermined wavelength λ_1 in a predetermined wavelength band, the loss $L(\lambda)$ and gradient $S(\lambda)$ in the wavelength band can be changed. As will be described later, the gradient $S(\lambda)$ of the optical filter 1 has small dependence on the wavelength λ , and the linearity of the loss $L(\lambda)$ of the optical filter 1 with respect to the wavelength λ is excellent.

The present inventor prepared several types of optical filters 1 by changing the structural parameters of the Mach-Zehnder interferometers 41 and 42 and confirmed the variability of the gradient $S(\lambda)$. The result will be described below.

A table below show the structural parameters in examples.

		Example A	Example B	Example C
First Mach-Zehnder Interference Circuit	A	0.60	0.85	0.60
	λ_0	1550	1550	1590
	$\Delta\lambda$	200	200	200
Second Mach-Zehnder Interference Circuit	A	0.50	0.60	0.5
	λ_0	1600	1600	1640
	$\Delta\lambda$	200	200	200

In the optical filters of all examples, the optical path lengths in the Mach-Zehnder interference circuits 41 and 42 were set to $12.5\lambda_0$ and $9.5\lambda_0$ at reference temperature. Under these conditions, the heaters 51 and 53 were operated to adjust the temperatures in the second region B and fifth region E of the main optical path 20, respectively, thereby changing the phase values $\Delta\phi$ of the Mach-Zehnder interference circuits 41 and 42 within the range of 0 rad to 0.595 rad such that the phase values had opposite signs and equal absolute values.

Figs. 4 to 6 are graphs showing loss spectra obtained when the phase value $\Delta\phi$ was changed in the optical filters of Examples A to C.

As is apparent from Fig. 4, in Example A, the loss ranges from 2.37 to 3.01 dB, i.e., is almost constant near the central wavelength of 1,550 nm in the wavelength band of 1,535 to 1,565 nm, and the gradient $S(\lambda)$ can be set within the range of 0 to 5.05 dB/30 nm in the wavelength band. When the phase value $\Delta\phi$ is 0.595 rad, the maximum value of the deviation from a straight line passing through a point corresponding to a loss of 2.89 dB (@central wavelength: 1,550 nm) is sufficiently as small as ± 0.21 dB. Thus, it was confirmed that the gradient $S(\lambda)$ is excellent in linearity.

As is apparent from Fig. 5, in Example B, the loss ranges from 3.65 to 3.98 dB, i.e., is almost constant near the central wavelength of 1,550 nm in the wavelength band of 1,535 to 1,565 nm, and the gradient $S(\lambda)$ can be set within the range of 0 to 10 dB/30 nm in the wavelength band. When the phase value $\Delta\phi$ is 0.314 rad, the maximum value of the deviation from a straight line passing through a point corresponding to a loss of 0.87 dB (@central wavelength: 1,550 nm) is sufficiently as small as ± 0.87 dB. Thus, it was confirmed that the gradient $S(\lambda)$ is excellent in linearity.

As is apparent from Fig. 6, in Example C, the loss ranges from 2.73 to 3.01 dB, i.e., is almost constant near the central wavelength of 1,590 nm in the

wavelength band of 1,575 to 1,605 nm, and the gradient $S(\lambda)$ can be set within the range of 0 to 5 dB/30 nm in the wavelength band. When the phase value $\Delta\phi$ is 0.595 rad, the maximum value of the deviation from a straight line passing through a point corresponding to a loss of 2.89 dB (@central wavelength: 1,590 nm) is sufficiently as small as ± 0.21 dB. Thus, it was confirmed that the gradient $S(\lambda)$ is excellent in linearity.

When the structural parameters of the Mach-Zehnder interference circuits 41 and 42 are appropriately set such that the phase value $\Delta\phi$ is set to 0 by adjusting the temperatures in the second region B and fifth region E of the main optical path 20 to predetermined bias temperatures, the phase value $\Delta\phi$ can be changed within the range of 0 to +0.595 rad by making the temperatures in the second region B and fifth region E of the main optical path 20 higher than the bias temperatures. In addition, the phase value $\Delta\phi$ can be changed within the range of -0.595 to 0 rad by making the temperatures in the second region B and fifth region E of the main optical path 20 lower than the bias temperatures. When the phase value $\Delta\phi$ is changed within the range of -0.595 to +0.595 rad, the gradient $S(\lambda)$ can be set within the range of $\pm a$ dB/nm in a predetermined wavelength band.

When Peltier elements are used in place of the

heaters 51 and 53 to raise or lower the temperatures in the second region B and fifth region E of the main optical path 20, the phase value $\Delta\phi$ can be set not only to a positive value but also to a negative value. This also makes it possible to change the phase value $\Delta\phi$ within the range of -0.595 to $+0.595$ rad.

As described above, in the optical filter 140 shown in Fig. 3, the loss spectrum for light input to the optical input terminal 11 and output from the optical output terminal 12 through the main optical path 20 is determined by the transmittance characteristic of the first Mach-Zehnder interference circuit 41 based on optical coupling between the main optical path 20 and the first sub optical path 21 by the optical couplers 31 and 32 and the transmittance characteristic of the second Mach-Zehnder interferometer 42 based on optical coupling between the main optical path 20 and the second sub optical path 22 by the optical couplers 33 and 34. This optical filter 140 is preferable because it is integrated on the substrate 10 and has a compact structure and also because of its small insertion loss.

Operation of the optical amplifier 100 according to the first embodiment will be described next, and an optical amplifier control method according to the first embodiment will be described. Figs. 7A to 7D are views

for explaining operation of the optical amplifier 100 according to the first embodiment. As for the loss spectrum (Fig. 7A) of the optical filter 140, as described above, the loss $L(\lambda)$ is almost constant at the predetermined wavelength λ_1 in the wavelength band of signal light, and the gradient $S(\lambda)$ is variable in the wavelength band. The gradient $S(\lambda)$ is controlled by the control circuit 150 which monitors the input signal light power.

Assume that the input signal light power has a predetermined value, and the gain of optical amplification of signal light by the input-side optical amplification section 111 and output-side optical amplification section 112 is almost constant independently of the wavelength (Fig. 7B). In this case, when the input signal light power becomes smaller than the predetermined value, the gain of optical amplification of signal light by the input-side optical amplification section 111 and output-side optical amplification section 112 is controlled by the control circuit 150 and becomes large. As a consequence, the longer the wavelength is, the smaller the gain becomes: the gain has wavelength dependence (Fig. 7C). At this time, however, the gradient $S(\lambda)$ of the optical filter 140 is controlled by the control circuit 150. The longer the wavelength is, the smaller the loss is set.

Hence, the wavelength dependence of gain of the input-side optical amplification section 111 and output-side optical amplification section 112 is canceled by the wavelength dependence of loss of the optical filter 140. As a result, the gain characteristic of the entire optical amplifier 100 becomes almost constant independently of the wavelength, and the gain flatness is maintained (Fig. 7D).

As described above, in this embodiment, even when the input signal light power varies, the output signal light power can be maintained at a predetermined target value, and the gain flatness of the entire optical amplifier 100 can be maintained. In addition, since the loss of the optical filter 140 is almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. In this embodiment, the optical filter 140 may be located on the output side of the output-side optical amplification section 112.

(Second Embodiment)

Fig. 8 is a schematic view showing the arrangement of an optical amplifier 200 according to the second embodiment of the present invention. Fig. 8 also illustrates an optical amplifier 200A provided on the input side of the optical amplifier 200. In the optical amplifier 200 according to this embodiment, an

optical coupler 230, input-side optical amplification section 211, optical filter 240, and output-side optical amplification section 212 are sequentially connected in series between an optical input terminal 201 and an optical output terminal 202. The optical amplifier 200 also has optical pumping light sources 221 and 222 for supplying optical pumping light to the input-side optical amplification section 211 and output-side optical amplification section 212, respectively, and a control circuit 250 for controlling the optical pumping light sources 221 and 222 and the loss spectrum of the optical filter 240.

The arrangement of each element is the same as in the first embodiment except the control circuit 250.

The control circuit 250 detects the power of input signal light demultiplexed by the optical coupler 230, as in the first embodiment, and also receives information related to the power of signal light output from the optical amplifier 200A on the input side, which is transmitted from the optical amplifier 200A on the input side. The control circuit 250 calculates the necessary gain on the basis of the output signal light power of the input-side optical amplifier 200A and the input signal light power of the optical amplifier of its own and controls the powers of optical pumping light to be output from the optical pumping light

sources 221 and 222 such that the power of output
signal light has a predetermined target value. The
control circuit 250 also controls the loss spectrum of
the optical filter 240 on the basis of the necessary
gain.

More specifically, when the necessary gain becomes
large, the gain of optical amplification of signal
light by the input-side optical amplification section
211 and output-side optical amplification section 212
becomes smaller as the wavelength becomes long; the
gain has wavelength dependence. At this time, however,
the gradient $S(\lambda)$ of the optical filter 240 is
controlled by the control circuit 250 so that the
longer the wavelength is, the smaller the loss becomes.
Hence, the wavelength dependence of gain of the
input-side optical amplification section 211 and
output-side optical amplification section 212 is
canceled by the loss spectrum of the optical filter 240.
As a result, the gain characteristic of the entire
optical amplifier 200 becomes almost constant
independently of the wavelength, and the gain flatness
is maintained.

As described above, in this embodiment as well,
even when the input signal light power varies, the
output signal light power can be maintained at a target
value, and the gain flatness of the entire optical

amplifier 200 can be maintained. In addition, since the loss of the optical filter 240 is almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. In this embodiment, the optical filter 240 may be located on the output side of the output-side optical amplification section 212.

(Third Embodiment)

Fig. 9 is a schematic view showing the arrangement of an optical amplifier 300 according to the third embodiment of the present invention. In the optical amplifier 300 according to this embodiment, an optical coupler 331, input-side optical amplification section 311, output-side optical amplification section 312, optical filter 340, and optical coupler 332 are sequentially connected in series between an optical input terminal 301 and an optical output terminal 302. The optical amplifier 300 also has optical pumping light sources 321 and 322 for supplying optical pumping light to the input-side optical amplification section 311 and output-side optical amplification section 312, respectively, and a control circuit 350 for controlling the optical pumping light sources 321 and 322 and the loss spectrum of the optical filter 340.

The arrangement of each constituent element is the same as in the first embodiment, and a detailed

description thereof will be omitted. As characteristic features of this embodiment, the optical coupler 332 is arranged on the light output side to supply a demultiplexed part of output light to the control circuit 350, and the optical filter 340 is arranged on the downstream side of the multi-stage optical amplifiers 311 and 312.

The control circuit 350 detects the power of input signal light demultiplexed by the optical coupler 331 and detects the power of output signal light demultiplexed by the optical coupler 332. The control circuit 350 controls the powers of optical pumping light to be output from the optical pumping light sources 321 and 322 such that the power of output signal light has a predetermined target value. The control circuit 350 calculates the gain on the basis of the output signal light power and input signal light power and controls the loss spectrum of the optical filter 340 on the basis of the gain.

More specifically, when the gain becomes large, the gain of optical amplification of signal light by the input-side optical amplification section 311 and output-side optical amplification section 312 becomes smaller as the wavelength becomes long; the gain has wavelength dependence. At this time, however, the gradient $S(\lambda)$ of the optical filter 340 is controlled

by the control circuit 350 so that the longer the wavelength is, the smaller the loss becomes. Hence, the wavelength dependence of gain of the input-side optical amplification section 311 and output-side optical amplification section 312 is canceled by the loss spectrum of the optical filter 340. As a result, the gain characteristic of the entire optical amplifier 300 becomes almost constant independently of the wavelength, and the gain flatness is maintained.

As described above, in this embodiment as well, even when the input signal light power varies, the output signal light power can be maintained at a target value, and the gain flatness of the entire optical amplifier 300 can be maintained. In addition, since the loss of the optical filter 340 is almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. In this embodiment, the optical filter 340 may be located between the input-side optical amplification section 311 and the output-side optical amplification section 312.

(Fourth Embodiment)

Fig. 10A is a schematic view showing the arrangement of an optical amplifier 400 according to the fourth embodiment of the present invention. In the optical amplifier 400 according to this embodiment, an

input-side optical amplification section 411,
output-side optical amplification section 412, and
optical filter 440 are sequentially connected in series
between an optical input terminal 401 and an optical
output terminal 402. The optical amplifier 400 also
has optical pumping light sources 421 and 422 for
supplying optical pumping light to the input-side
optical amplification section 411 and output-side
optical amplification section 412, respectively, a
spectrum monitor device 460 for monitoring the powers
of signal light components with respective wavelengths,
which are output from the optical output terminal 402,
and a control circuit 450 for controlling the optical
pumping light outputs from the optical pumping light
sources 421 and 422 and the loss spectrum of the
optical filter 440.

As a characteristic feature of this embodiment,
the spectrum monitor device 460 is used. The
arrangements of the remaining elements are the same as
in the above embodiments, and a detailed description
thereof will be omitted.

Part of light output from the optical output
terminal 402 is demultiplexed and guided to the
spectrum monitor device 460, or light output from a
second sub optical path 22 of the optical filter 440
having the structure shown in Fig. 3 is guided to the

spectrum monitor device 460, and the guided light is demultiplexed by the spectrum monitor device 460. This spectrum monitor device 460 can be implemented by, e.g., an AWG (Arrayed-Waveguide Grating). In this case, the spectrum monitor device 460 can be formed on a common substrate together with the optical filter 440 having the structure shown in Fig. 3, so the entire device can be downsized.

The control circuit 450 controls the power of output signal light component with respective wavelengths, which are demultiplexed by the spectrum monitor device 460. The control circuit 450 controls the powers of optical pumping light to be output from the optical pumping light sources 421 and 422 such that the power of output signal light has a predetermined target value. The control circuit 450 also controls the loss spectrum of the optical filter 440 on the basis of any deviation between the powers of output signal light components with respective wavelengths such that the deviation becomes small.

Preferred examples of the optical filter 440 and spectrum monitor device 460 will be described. Fig. 11 is an explanatory view of the optical filter 440 and spectrum monitor device 460. The optical filter 440 and spectrum monitor device 460 are formed on a common substrate 10A. The optical filter 440 has the same

structure as that shown in Fig. 3. The spectrum monitor device 460 is formed from an AWG formed on the substrate 10A. More specifically, the spectrum monitor device 460 has an input-side slab waveguide 61, array waveguide section 62 having a plurality of channel waveguides, output-side slab waveguide 63, and output-side channel waveguides 64_1 to 64_N .

Light output from the second sub optical path 22 of the optical filter 440 is input to the input-side slab waveguide 61. The light is demultiplexed and output to the channel waveguides of the array waveguide section 62. The plurality of channel waveguides of the array waveguide section 62 have different optical path lengths from the input-side slab waveguide 61 to the output-side slab waveguide 63 and give different phases to the light to be guided. The output-side slab waveguide 63 receives light from each of the plurality of channel waveguides of the array waveguide section 62 and outputs the light to each of the output-side channel waveguides 64_1 to 64_N .

The light components output to the output-side channel waveguides 64_1 to 64_N are signal light components having respective wavelengths, which are obtained by demultiplexing the light output from the second sub optical path 22 of the optical filter 440. The control circuit 450 detects the powers of signal light

components having respective wavelengths, which are
output to the output-side channel waveguides 64₁ to 64_n
of the spectrum monitor device 460, and controls the
loss gradient of the optical filter 440 such that the
deviation between the powers of signal light components
having respective wavelengths becomes small. The
control circuit 450 may control the loss gradient of
the optical filter 440 such that the deviation between
powers of two signal light components having respective
wavelengths (e.g., the maximum wavelength and minimum
wavelength) in the signal light components having
respective wavelengths, which are demultiplexed by the
spectrum monitor device 460.

Fig. 10B shows a modification to the fourth
embodiment. A difference from the fourth embodiment
shown in Fig. 10A is that an optical coupler 430 for
demultiplexing a monitor light component in the input
signal light is arranged on the optical input terminal
401 side. Monitor light contains, e.g., information
related to the shortest wavelength and longest
wavelength in the sent multiplexed signal light. The
control circuit 450 reads the pieces of information and
determines the two wavelengths for which the power
deviation is to be obtained.

As described above, in this embodiment as well,
even when the input signal light power varies, the

output signal light power can be maintained at a predetermined target value, and the gain flatness of the entire optical amplifier 400 can be maintained. In addition, since the loss of the optical filter 440 is almost constant at a predetermined wavelength in the wavelength band of signal light, the noise factor does not degrade. Furthermore, in this embodiment, since the loss gradient of the optical filter 440 is feedback-controlled, stable operation is possible.

(Fifth Embodiment)

Fig. 12 a schematic view showing the arrangement of an optical amplifier 500 according to the fifth embodiment of the present invention. In the optical amplifier 500 according to this embodiment, a gain equalizer 170 is inserted between an input-side optical amplification section 111 and an optical filter 140 of the optical amplifier 100 according to the first embodiment. The gain equalizer 170 equalizes gain wavelength dependence unique to the input-side optical amplification section 111 and output-side optical amplification section 112. This gain equalizer 170 can be implemented by, e.g., an optical fiber grating element having index modulation in the core of an optical fiber or an etalon filter having a Fabry-Perot resonator structure.

The operation of the optical amplifier 500

according to the fifth embodiment, i.e., an optical amplification method according to the fifth embodiment will be described next. Figs. 13A to 13C are views for explaining the operation of the optical amplifier 500 according to the fifth embodiment. Even when the input signal light power has a predetermined value, the gain spectrum of the input-side optical amplification section 111 and output-side optical amplification section 112 is not strictly constant and has a gain wavelength dependence unique to the input-side optical amplification section 111 and output-side optical amplification section 112 (Fig. 13A). The gain equalizer 170 has a loss spectrum having the same shape as that of the gain spectrum of the input-side optical amplification section 111 and output-side optical amplification section 112 at this time. Hence, the spectrum of output light is flat.

When the input signal light power has a value smaller than the predetermined value, the gain of optical amplification of signal light by the input-side optical amplification section 111 and output-side optical amplification section 112 is controlled by a control circuit 150 and becomes large. Consequently, the longer the wavelength becomes, the smaller the gain becomes, so the wavelength dependence of gain changes (Fig. 13B). At this time, however, the loss spectrum

of the optical filter 140 is controlled and set by the control circuit 150 such that the longer the wavelength is, the smaller the gain becomes.

For the light output from the input-side optical amplification section 111 and output-side optical amplification section 112, the gain wavelength dependence unique thereto is equalized by the gain equalizer 170, so the gain (dB) is adjusted to linearly change with respect to the wavelength, as shown in Fig. 13C. After that, the remaining wavelength dependence of gain is canceled by the loss spectrum of the optical filter 140. As a result, the gain characteristic of the entire optical amplifier 500 is almost constant independently of the wavelength, and its flatness is maintained.

As described above, in this embodiment as well, even when the input signal light power varies, the output signal light power can be maintained at a predetermined target value, and the gain flatness of the entire optical amplifier 500 can be maintained. Especially in this embodiment, since the gain equalizer 170 is provided in addition to the optical filter 140, the gain flatness of the entire optical amplifier 500 is excellent. In addition, since the loss of the optical filter 140 is almost constant at a predetermined wavelength in the wavelength band of

signal light, the noise factor does not degrade. In this embodiment, one or both of the optical filter 140 and gain equalizer 170 may be located on the output side of the output-side optical amplification section 112. The same effect as described above can be obtained even when a gain equalizer is inserted in any one of the optical amplifiers according to the second to fourth embodiments.

(Sixth Embodiment)

Fig. 14A is a schematic view showing the arrangement of an optical amplifier 300a according to the sixth embodiment of the present invention. The optical amplifier 300a according to this embodiment is different from the optical amplifier 300 according to the third embodiment shown in Fig. 9 only in that an ASE light level detector 333 is arranged in place of the optical coupler 332 at the final stage.

The ASE light level detector 333 detects the level of spontaneous emission light (ASE light) having respective wavelengths located outside the two ends of a predetermined wavelength band of signal light output from an optical filter 340. A control circuit 350 adjusts the loss spectrum of the optical filter 340 such that the difference in the detected ASE light level between the longest wavelength side and the shortest wavelength side is maintained at a

predetermined value. Use of the level difference in ASE light advantageously facilitates control.

When monitor light having information related to the shortest wavelength and longest wavelength in multiplexed signal light is sent together with the multiplexed signal light, monitor light demultiplexed by an optical coupler 331 is received by the control circuit 350 to read the pieces of information, and wavelengths for which the ASE light levels are to be detected by the ASE light level detector 333 are set to those outside the read shortest wavelength and longest wavelength. In this case, even when the shortest wavelength and longest wavelength in the multiplexed signal light are not constant, stable optical amplification can be performed.

Fig. 14B is a schematic view showing the arrangement of an optical amplifier 600 as a modification to the sixth embodiment of the present invention. More specifically, an optical coupler 630, input-side optical amplification section 611, output-side optical amplification section 612, optical coupler 631, and optical filter 640 are sequentially connected in series between an optical input terminal 601 and an optical output terminal 602. The optical amplifier 600 also has optical pumping light sources 621 and 622 for supplying optical pumping light to the

input- and output-side optical amplification sections 611 and 112, respectively, and a control circuit 650 for controlling the light powers of the optical pumping light sources 621 and 622 and the loss spectrum of the optical filter 640. Light demultiplexed by the optical coupler 631 is guided to a spectrum monitor device 660 and variable bandpass filter 670. The light transmitted through the variable bandpass filter 670 is detected by a light-receiving element 680. The arrangements of the amplification sections 611 and 612 and the optical filter 640 are the same as in the first embodiment, and a detailed description thereof will be omitted.

In this embodiment, the wavelengths of light with the shortest wavelength and light with the longest wavelength in the signal light are detected by the spectrum monitor device 660. By controlling the variable bandpass filter 670, the ASE light levels on the shorter wavelength side of the detected shortest wavelength and on the longer wavelength side of the detected longest wavelength are detected by the light-receiving element 680. The control circuit 650 adjusts the loss spectrum of the optical filter 640 such that the difference in detected ASE light levels between the longer wavelength side and the shorter wavelength side is maintained at a predetermined value.

This also facilitates control.

(Seventh Embodiment)

Fig. 15 is a schematic view showing the arrangement of an optical amplifier 700 according to the seventh embodiment of the present invention. This optical amplifier 700 incorporates a DCF (Dispersion Compensating Fiber) 770.

More specifically, an optical coupler 730, input-side optical amplification section 711, optical filter 740, intermediate optical amplification section 712, gain equalizer 760, DCF 770, and output-side optical amplification section 713 are sequentially connected in series between an optical input terminal 701 and an optical output terminal 702. The optical amplifier 700 also has optical pumping light sources 721 to 723 for supplying optical pumping light to the input-side, intermediate, and output-side optical amplification sections 711 to 713, respectively, and a control circuit 750 for controlling the light powers of the optical pumping light sources 721 to 723 and the loss spectrum of the optical filter 740. The arrangements of the optical amplification sections 711 to 713 and optical filter 740 are the same as in the first embodiment, and a detailed description thereof will be omitted.

To confirm the noise characteristic improving

effect of the optical amplifier 700 according to this embodiment using an optical filter capable of adjusting the loss spectrum, the present inventor conducted comparative experiments for a case wherein a conventional variable optical attenuator for adjusting only the total loss ratio is used as an optical filter.

In the experiments, the noise characteristic with respect to the input level in a dynamic range of 16 dB from -28 dbm/ch to -12 dbm/ch was measured. When the variable optical attenuator is used, it is generally difficult to cope with an input dynamic range of 16 dB. Hence, measurement was performed by dividing the range into two parts: -28 dbm/ch to -20 dbm/ch and -20 dbm/ch to -12 dbm/ch, and also for a combination thereof.

Fig. 16 shows the measurement results. Referring to Fig. 16, ○ indicates a noise characteristic with respect to the input level, which was obtained when the total range was amplified by one type of optical amplifier using the variable optical attenuator, △ indicates a noise characteristic with respect to the input level, which was obtained when the total range was divided and amplified by two types of optical amplifiers using the variable optical attenuator, and □ indicates a noise characteristic with respect to the input level, which was obtained when the total range was amplified by the optical amplifier according to the

seventh embodiment of the present invention.

It was confirmed that the optical amplifier according to the present invention has an effect for improving the noise characteristic at all input levels and widening the adaptable dynamic range.

A modification of the optical filter will be described next. Each of the optical filters having the loss spectra shown in Figs. 4 to 6 has an almost constant loss near the central wavelength of the use wavelength band. However, the wavelength λ_1 at which the loss becomes almost constant may be shifted to the shorter wavelength side or longer wavelength side. For an optical filter having a loss spectrum shown in Fig. 17, the wavelength λ_1 is located at the shortest wavelength in the wavelength band. The loss spectrum can be changed between and $L_0(\lambda)$ and $L_2(\lambda)$. When the power of light input to the optical filter is maximum, the loss spectrum is adjusted to $L_2(\lambda)$. When the power of input light is minimum, the loss spectrum is adjusted to $L_0(\lambda)$ at which the loss becomes constant independently of the wavelength. For intermediate power, the loss spectrum is adjusted to $L_1(\lambda)$. Thus, degradation in noise factor especially in the short wavelength region can be suppressed. When the input power is minimum, the transmittance is maximized. Hence, the noise characteristic improving effect

becomes conspicuous especially when the power of input light is small.

(Eighth Embodiment)

Fig. 18 is a schematic view showing the arrangement of an optical amplifier 300b according to the eighth embodiment of the present invention. The optical amplifier 300b according to this embodiment is different from the optical amplifier 300 of the third embodiment shown in Fig. 9 in that a wave number monitor 335 for detecting the number of signal light components (wave number) contained in output multiplexed signal light is arranged at the demultiplexed side of an optical coupler 332 at the final stage.

When the number of waves contained in input multiplexed signal light varies, the power of the input multiplexed signal light varies, though the powers of individual signal light components do not vary. For this reason, when the power of output multiplexed signal light after amplification is to be simply maintained at a predetermined value, the powers of individual signal light components increase in case of a decrease in wave number, or the powers of individual signal light components decrease in case of an increase in wave number, resulting in variation.

In this embodiment, the target value of power of

output multiplexed signal light is adjusted by a control circuit 350b in proportion to the wave number on the basis of the output from the wave number monitor 335. Thus, even when the wave number varies, the light power after the individual signal light components are amplified can be maintained at a predetermined value.

The present invention is not limited to the above embodiments, and various changes and modifications can be made. For example, the fluorescent material to doped into the amplification optical fiber is not limited to Er, and another rare earth element (e.g., Tm, Pr, Nd, or the like) may be used. Instead of the amplification optical fiber, a planar optical waveguide doped with a fluorescent material that can be excited by optical pumping light may be used. The optical amplifier need not always be divided into the input-side optical amplification section and output-side optical amplification section and may have three or more optical amplification sections.